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Experiments on Column Base Stiffness of Long-Span Cold-Formed Steel Portal Frames Composed of Double Channels

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Abstract

Cold-formed steel haunched portal frames are popular structures in industrial and housing applications. They are mostly used as sheds, garages, and shelters, and are common in rural areas. Cold-formed steel portal frames with spans of up to 30m (100 ft) are now being constructed in Australia. As these large structures are fairly new to the market, there is limited data on their feasibility and design recommendations. An experimental program was carried out on a series of portal frame systems composed of back-to-back channels for the columns, rafters, and knee braces. The system consisted of three frames connected in parallel with purlins to simulate a free standing structure, with an approximate span of 14 m (46 ft), column height of 5.3 m (17 ft), and apex height of 7 m (23 ft). Several configurations were tested including variations in the knee connection, sleeve stiffeners in the columns and rafters, and loading of either vertical or combined horizontal and vertical loads. Deflections were recorded at various locations to measure global and local movements of the structural members, as well as column base reactions and base rotations. It was determined that the column bases are semi-rigid and further column base connection tests were completed to quantify column base connection stiffness for bending about the column major and minor axes, as well as twist. Results of the column base connection stiffness are presented as well as the implications for frame design.

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Introduction

Cold-formed steel haunched portal frames are prevalent structures in housing and industrial uses, especially in rural regions in Australia. There is a demand for the construction of larger spans; however there is a lack of test data on their performance. Previous experimental studies have been conducted on medium span double channel portal frames (Lim & Nethercot 2002, Stratan et al. 2006, Zhang 2014, Wrzesien et al. 2012) consisting of either a single frame or bay. The experimental work discussed herein aims to expand the data available to larger spans and multiple bays.

A series of full scale experiments on long-span cold-formed steel portal frames has been conducted by the authors. Further details of the experimental program can be found elsewhere (Blum & Rasmussen 2016a,b,c). It was found during the experimental program that column base connections produced semi-rigid behavior. Previous studies have been conducted on cold-formed steel portal frame base fixity (Robertson 1991, Kwon et al. 2004) for other types of base connections. Therefore individual column base connection tests were completed to quantify the rotational stiffness for bending about the column major and minor axes, as well as the column base restraint to torsion.

Full Scale Experiments

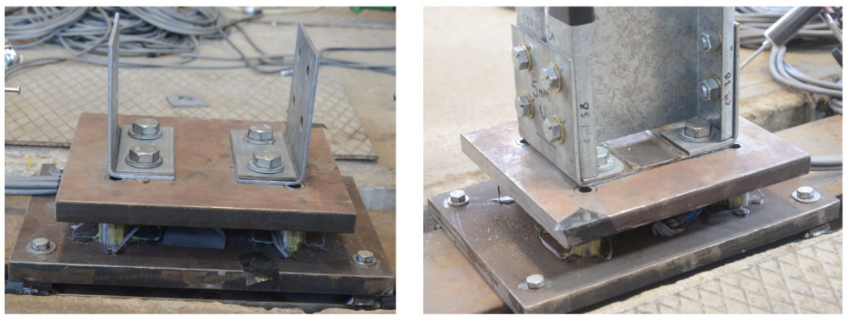
Layout and load application

An experimental program was carried out on a series of haunched portal frame systems composed of back-to-back channels bolted through the webs for the columns, rafters, and knee braces. Members were connected together with double L brackets bolted through the webs. The test frame had a centerline span of 13.6 m (44.6 ft) and a height of 6.6 m (21.7 ft), the rafters were inclined at an angle of 10° from the horizontal, and there was a 50° angle between the column and knee brace. The experimental setup consisted of three frames connected in parallel with purlins between the rafters to create a free standing 2 bay structure with a bay spacing of 3.6 m (11.8 ft); however load was applied only to the center frame, with the outer frames serving as supports providing lateral restraints to the center frame representative of industry practice. Cross-bracing was connected on both sides of one bay. The setup is shown in Figure 1.

A total of nine frames were tested: eight with unbraced columns and one with braced columns. Half of the unbraced column tests were with vertical loads only and half were tested with horizontal and vertical loads. Several configurations of frames were tested, including variations in the knee connections and the addition of sleeve stiffeners. Vertical load was applied through a hydraulic jack, which was connected to a load spreading system consisting of a series of HSS, rods, and bars, to distribute the load from the jack to eight points along the rafter, thus simulating a uniformly distributed vertical load. A horizontal jack was connected to a trolley, to which the main vertical jack was mounted, and was controlled by a transducer at the apex which measured frame sway. The horizontal jack moved equally with the frame sway, therefore maintaining the main jack in a vertical position. In the four tests subject to horizontal and vertical loads, the horizontal loads representing wind loads were simulated by hanging a 5 kN (1.12 kip) concrete block off the side of the frame. A thick plate was bolted to the north column eaves brackets. The concrete block was connected to this plate through a cable and pulley system. The block was slowly lowered first, and then vertical loads were applied until failure under constant horizontal load.

Figure 1: Experimental frame setup

The column base connection consisted of two 5 mm (0.20 in) thick L plates with washers bolted to the column flanges. The L plates were connected to the strong floor through finger clamps, and the connection is shown in Figure 2. In practice, the L cleat and washer would be connected to hold-down bolts encased in a concrete foundation. The focus of this paper is on the semi-rigidity of this column base connection.



(a) (b)

Figure 2: Column base connection (a) L brackets and (b) U bracket

Instrumentation

Transducers were placed at various locations on the frame to measure global movements in three directions, twist, and local deformations. The instrumentation includes transducers at column mid-height, column at the knee connection, knee and knee connection brackets, eave connection, and apex connection. Further details can be found elsewhere [Blum & Rasmussen 2016c]. From experiment 3 onwards, four transducers were placed at the base of each column flange to measure column base rotation about the column major axis. The transducers were located in the middle between the bolt-holes in the base L plate, approximately 8 cm (3.15 in) up from the base. This transducer setup is shown in Figure 3.

For experiments 1-4, column base reactions were measured through strain gauges near the base. The strain gauges were located approximately 15 cm (5.9 in) up from the base of the column, on both inner and outer surfaces of all flanges, 20 mm (0.79 in) from the corner. The placement was to ensure that local effects from the column to base plate connection bolts did not affect the results. For experiments 5-9, fixed-end bearings were constructed to form load cells to measure column base reactions of axial force and bending moments about the column major and minor axes.

The resulting data from the column base transducers and strain gauges or column base load cells allowed the calculation of column base major axis moment-rotation curves during the full scale experiments.

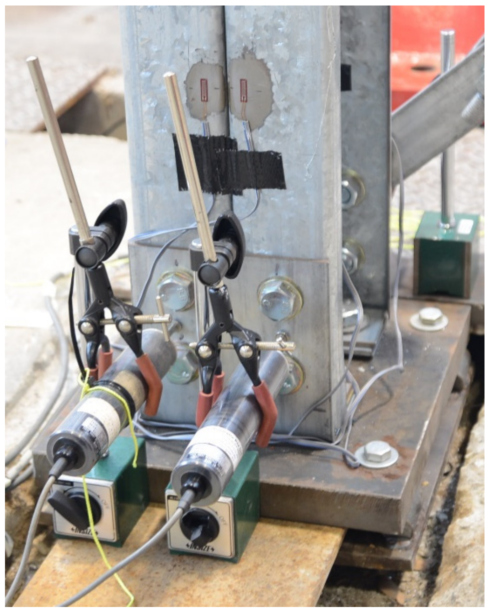


Figure 3: Instrumentation on column base connection

Moment-rotation results for full scale experiments

A plot of moment vs rotation at the column base is presented in Figure 4 for experiments 5 and 6. Experiment 5 had gravity loads only applied, while experiment 6 had a 5 kN (1.12 kip) wind load applied followed by gravity load until failure. The wind load produced a base moment of approximately 4 kNm (35.4 kip-in) in the north column and 3 kNm (26.6 kip-in) in the south column. The results for both of these experiments are characteristic of the other experiments. More details can be found elsewhere (Blum & Rasmussen 2016c). The moment-rotation curves have an initial linear region up to approximately 1 or 1.5 kNm (8.85 or 13.3 kip-in), followed by a non-linear region, and lastly a linear region beginning between 3 and 4 kNm. The jumpiness in the plot for the north column of experiment 6 is due to the manual release of the concrete block used to simulate wind loading. The column base stiffness of the initial linear region is given in Table 1 for experiments 3 to 9.

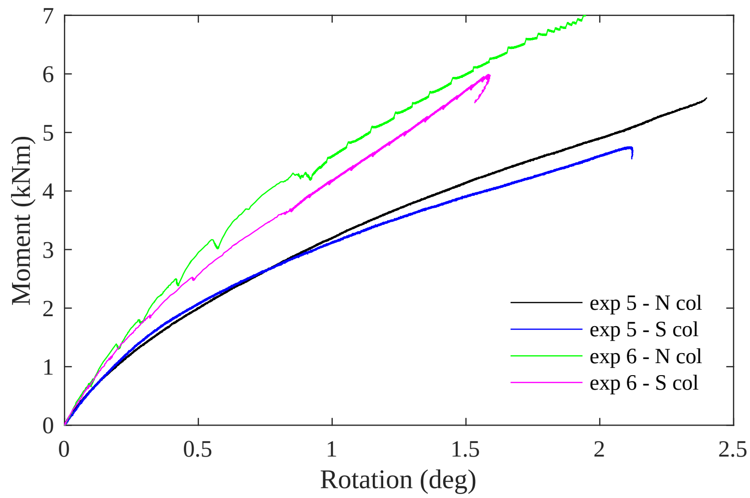


Figure 4: Column base moment vs rotation for bending about column major axis for experiments 5 and 6

Base Connection Tests

Separate column base rotation tests have been completed to quantify the base stiffness for bending about the column major axis and minor axis. Various base plate connections have been tested to determine their effect on column base stiffness, including 5 mm (0.20 in), 6 mm (0.24 in), and 8 mm (0.31 in) L-plates and a 5 mm U-plate. The U-plate was created by welding a plate of mild steel in between 2 L-plates to form one section, as shown in Figure 2(b).

Two columns were cut to 1.6 m (63 in) lengths and both columns were tested with the various base plates. Load was applied approximately 1270 mm (50 in) from the column base through a jack. Transducers approximately 80 mm (3.1 in) above the column bases were used to measure column base rotations. The columns were loaded and unloaded for two cycles. Data from the second loading cycle was utilized to avoid the influence of any possible initial settlement of the connections during the first loading cycle. Setups for base rotation tests for bending about the column major and minor axes are shown in Figure 5.

Column major axis, M_x

The column was loaded up to a moment of 6 kNm (53.1 kip-in) to correspond to the full scale experiments. Four transducers, located on the column base L-plates bolted to the channel flanges, were used to measure the column base rotation, and are shown in Figure 5(a). Results of the column base moment vs. rotation for the 2nd loading cycle are shown in Figure 6 for the various base plate connections for both column specimens.

(a) (b)

Figure 5: Column base rotation tests for bending about column (a) major axis and (b) minor axis

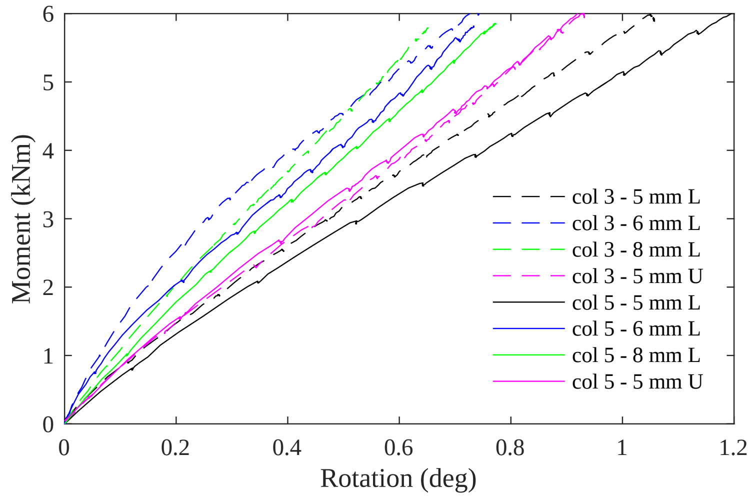


Figure 6: Column base moment vs rotation for bending about column major axis

The moment rotation curves are characterized by an initial non-linear region followed by a linear region starting approximately at an applied moment of 1 kNm (8.85 kip-in) for the 5 mm thick plates and 2 kNm (17.7 kip-in) for the 6 and 8 mm thick plates. A linear regression was fitted through the linear region of each moment-rotation curve. The resulting moment-rotation stiffness values are presented in Table 2.

Column minor axis, M_y

The column was loaded until it rotated around 1.2 degrees, as this matched rotations from the major axis bending test, and to prevent plastic deformations from occurring if additional load was applied. Load was applied from the jack to the column through 2 steel arms into the web-flange junctions, as shown in Figure 7(a). This arrangement distributed the load into the center of the built-up cross-section. Two transducers with L-bracket extensions were used to measure deflections at the web-flange junction, as shown in Figure 7(b), to avoid measuring local deflections of the channel section plate elements. Results of the column base moment vs. rotation for the 2nd loading cycle are shown in Figure 8 for the various base plate connections for both column specimens.

(a) (b)

Figure 7: Setup for column base rotation for bending about column minor axis (a) load application arms and (b) transducer extensions

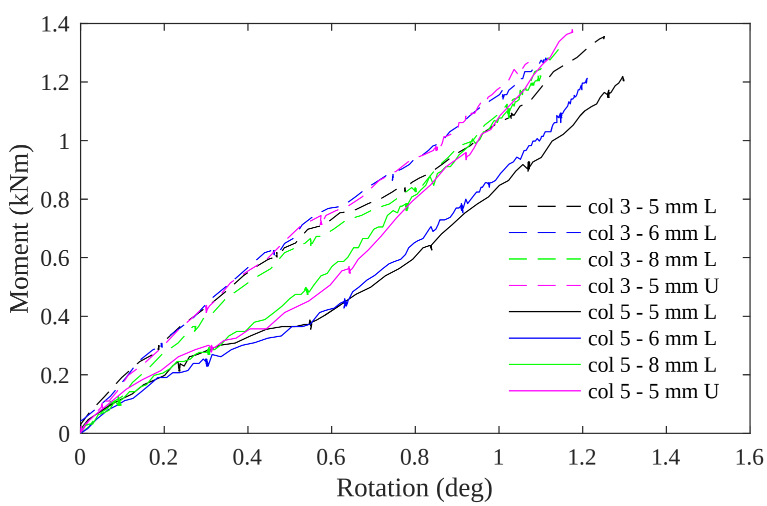


Figure 8: Column base moment vs rotation for bending about column minor axis

The moment rotation curves are characterized by an initial non-linear region followed by a linear region starting approximately at an applied moment of 0.5 kNm (4.43 kip-in). A linear regression was fitted through the linear regions of each moment-rotation curve. The resulting moment-rotation stiffness values are presented in Table 3.

Column base torsion test

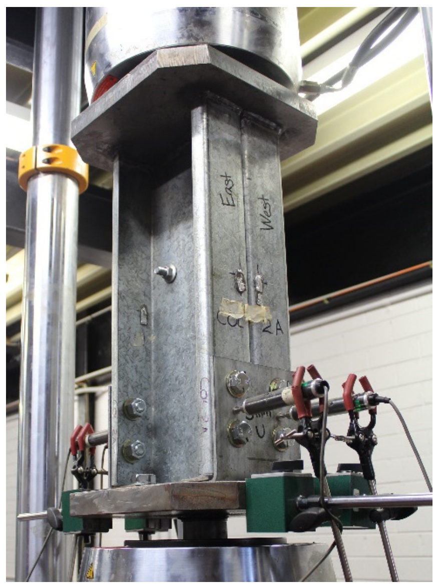


Figure 9: Setup for column base torsion test

One column was cut at the base to a 500 mm (19.7 in) length to fit inside the testing machine. The top end of the specimen was welded to a thick plate and was fixed inside the top grip of the machine. The base end of the column was bolted to a bottom thick plate through the column base L brackets. The bottom plate was twisted up to a moment of 2 kNm (17.7 kip-in) both clockwise and counter clockwise; as the results are identical the results from only one direction is plotted. Various base plate connections were tested including 5 mm and 6 mm L plates and a 5 mm U plate. Four transducers were placed 80 mm (3.1 in) above the column bases on the L brackets connected to the column flanges, as shown in

Figure 9. The transducers were attached to the rotating bottom thick plate, and therefore measured the relative rotation of the column at 80 mm up from the base to that of the base.

A twisting moment applied to a section is resisted by the uniform and nonuniform torsion components. Of these, the uniform torque is proportional to the thickness to a power of three and is considered to be an order of magnitude smaller than the warping torque for the section considered. Furthermore, as the column was bolted to two thick L plates, the connection was assumed to be fully clamped against twist rotations at the base. Hence, no warping displacements occurred and uniform torsion could be assumed to be zero at the column base. For these two reasons combined, the twist measured by the transducers was considered to be a result of nonuniform torsion only.

Warping displacements are proportional to the rate of change of twist of the section. Twist was measured at only two locations: at the base and 80 mm above the base. Without additional points only a linear relationship can be assumed, so therefore the rate of change of twist was calculated as twist divided by the height of the transducers. The twisting moment versus rate of twist of the section is plotted in Figure 10. The slope of this plot represents the warping restraint of the column base connection.

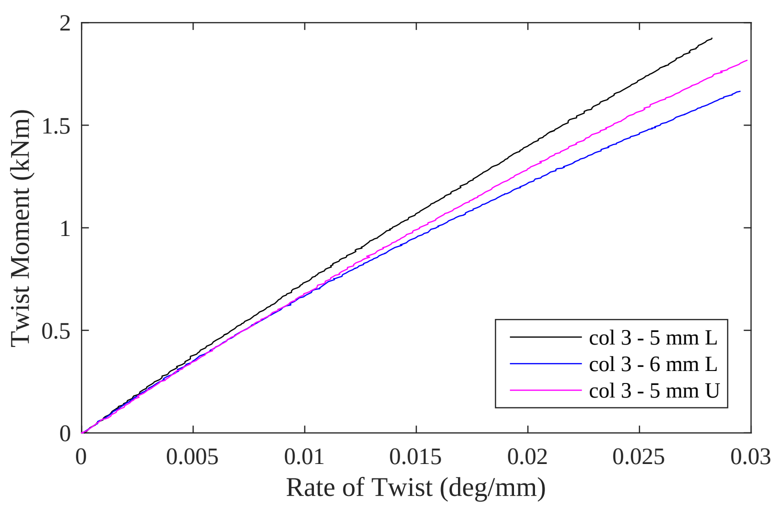


Figure 10: Column base twist moment vs rate of twist

As shown in Figure 10, the 6 mm thick L plates provide a less stiff connection than the 5 mm thick L plates. Unlike the base rotation tests for bending about the column major axis, thicker L plates do not make the connection more rigid in torsion as it does not depend on the bending of the L plate. Holes were drilled in the columns to fit the 5 mm L plates, thus the 6 mm L plates did not line up exactly with the bolt holes on the column flanges and were forced into position. While this has a negligible effect on the base rotation tests, it could provide an explanation for the less stiff connection that the 6 mm L brackets provide.

Results – Spring Stiffness

The column base stiffness for column major axis bending in the full scale experiments is given in Table 1 for both north and south columns for experiments 3 through 9. “Wind” loading indicates that the experiment had a constant wind load of 5 kN (1.12 kip) applied followed by gravity loads until frame failure, while “gravity” loading indicates that only gravity loading was applied. The base stiffness was estimated from the slope of the moment vs rotation plots for the initial linear region up to a moment of 1.5 kNm (13.3 kip-in). Finite element analyses have shown that using the initial column base stiffness yields good agreement between models and the experiments (Blum & Rasmussen 2016d).

Table 1: Column base stiffness for column major axis bending in full scale experiments

Experiment	Loading	Column	Column base stiffness	
			kNm / deg	kip-in / deg
3	Wind	N	7.27	64.3
		S	5.44	48.1
4	Wind	N	4.34	38.4
		S	3.47	30.7
5	Gravity	N	4.48	39.7
		S	4.98	44.1
6	Wind	N	5.56	49.2
		S	3.89	34.4
7	Gravity	N	3.29	29.1
		S	3.68	32.6
8	Wind	N	4.99	44.2
		S	4.92	43.5
9	Gravity	N	5.01	44.3
		S	6.25	55.3
Average			4.83	42.7

As shown in Figure 1, the frames in the full scale experiments supported a load spreading system, which weighed 4 kN (0.90 kip). This was attached to the frame prior to the start of the experiment. Therefore, there was already a reaction in the column bases prior to the recording of experimental data. Additionally, there was some minor shifting of the frames during construction, whereby any initial settlement of the connection already occurred prior to testing. For the small scale base rotation tests, loading began with no other loads already on the column. A finite element model was created in MASTAN2 (McGuire et al. 2000) with a semi-rigid column base for bending about the column major axis with a stiffness equal to the average as calculated from full scale experiments. It was determined that the load spreading system of 4 kN (0.90 kip) produced a moment reaction in the column base of approximately 1 kNm (8.85 kip-in). This also corresponds to the start of the linear region for the base rotation tests for the 5 mm thick plates. Therefore the base stiffness was calculated from the slope of the moment-rotation curves starting from 1 kNm for the 5 mm thick plates, and 2 kNm (17.7 kip-in) for the 6 and 8 mm thick plates, which was the start of the linear region for the thicker connections. The resulting base stiffness for bending about the column major axis is shown in Table 2. There is good agreement between the averages for the 5L connection between the full scale experiments and the smaller base connection tests.

Table 2: Column base stiffness for column major axis bending

Base	Stiffness, kNm/deg (kip-in/deg)			% inc. from
Connection	Col 3	Col 5	Average	5L conn.
5L	5.15	4.59	4.87 (43.1)	–
5U	6.25	6.15	6.25 (55.3)	28.3
6L	6.39	7.24	6.82 (60.4)	40.0
8L	8.24	7.13	7.69 (68.1)	57.9

As shown in Table 2, the thicker L-plates had an increased base stiffness of 40% and 58% for the 6 mm and 8 mm plates, respectively, and the 5 mm U-plate had an increase of 28% compared to the 5 mm L-plates. Therefore, the column base stiffness could be improved by using thicker L-plates or a U-plate.

The column base stiffness for bending about the column minor axis is presented in Table 3 for the various connections. As stated previously, the linear region began at approximately an applied moment of 0.5 kNm (4.43 kip-in). Overall, the column base connections were stiffer for column 5 than for column 3. When comparing the average column base stiffness for the various base plates there is a small increase in stiffness for thicker L-plates of 6% and 10% for the 6 mm and

8 mm thick plates, respectively, however the largest increase of 18% is due to the use of the 5 mm U-plate. This is a result of the U-plate being stiffer as it is a single section, as opposed to two separate L-plates which act independently.

Table 3: Column base stiffness for column minor axis bending

Base Connection	Stiffness, kNm/deg (kip-in/deg)			% inc. from 5L conn.
	Col 3	Col 5	Average	
5L	0.921	1.21	1.07 (9.47)	–
5U	1.04	1.48	1.26 (11.2)	18.3
6L	0.998	1.26	1.13 (10.0)	5.96
8L	1.05	1.30	1.18 (10.4)	10.3

Effects on frame ultimate load

Finite element studies have shown that base stiffness has a significantly larger impact on frame ultimate vertical load when wind loads are included, instead of applied vertical loads only (Blum & Rasmussen 2016d). In the experimental program, experiments 3 and 4 were nominally identical. However, the ultimate vertical load for experiment 3 was 19.5 kN (4.38 kip) while that of experiment 4 was 13.3 kN (2.99 kip). This is mostly attributable to the variation in base stiffness of the columns for bending about the column major axis, as shown in Table 1. A parametric study of the effect of column base stiffness on frame ultimate vertical load through a validated finite element analysis was conducted (Blum & Rasmussen 2016d) and shows the effect of column base stiffness on frame ultimate vertical load for vertical loads only and combined wind and vertical loads. It was found that the decrease in frame ultimate vertical load from the maximum base stiffness to minimum base stiffness as measured in experiments was 2.2% for applied vertical loads only, and 14.8% for applied wind and vertical loads. Therefore the value of the column base stiffness is crucial for accurate ultimate load predictions when wind loading is considered.

Design Considerations

As column base stiffness has a large impact on frame ultimate vertical load, especially when wind loading is considered, it is important to include the semi-rigidity of connections in the analysis of frames. A linear spring can be defined in finite element software such as ABAQUS (ABAQUS 2014) for rotations about the global x, y and z-axes, and MASTAN2 (McGuire 2000) for rotations about the element local y and z-axes. Therefore the semi-rigidity of the column bases for bending about the column major and minor axes as presented herein can be implemented into models. This will help to improve the accuracy of FEM predictions.

The torsional spring could be implemented into a finite element program which has 7 degrees of freedom per element, where degrees 1-3 are the displacements in x, y, and z directions, degrees 4-6 are the rotations about the x, y, and z axes, and degree 7 is the warping rotation. The data provided could be used to determine a spring stiffness for the warping rotation degree of freedom. However use of this approach would depend on the capabilities of the software under consideration.

Conclusions

A series of full scale experiments has been conducted on long-span cold-formed steel portal frames for several frame configurations and loading conditions. Column base reaction moments and rotations have been recorded for bending about the column major axis, and are presented herein. It was shown that there exists a variation in column base stiffness for nominally identical connections, and that frame ultimate vertical loads are sensitive to the base stiffness when wind loading is considered. Separate column base rotation tests of cold-formed steel portal frames have been completed to quantify the base stiffness for bending about the column major and minor axes, as well as twist. Various base plate connections have been tested including 5 mm, 6 mm, and 8 mm thick L-plates and a 5 mm U-plate. It was found that thicker L-plates at the base have a higher stiffness for bending about the column major axis, and the base U-plate has the highest stiffness for bending about the column minor axis. Implementation of this data into finite element models is discussed.

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References

ABAQUS, 2014. ABAQUS / Standard Version 6.14, Dassault Systemes, Providence, RI, USA.

Blum, H.B. & Rasmussen, K.J.R., 2016a. "Buckling and design of column with intermediate elastic torsional restraint." *Proc. Annual Stability Conference, Orlando, Florida, 12-15 April.*

Blum, H.B. & Rasmussen, K.J.R., 2016b. "Experiments on long-span cold-formed steel double-channel portal frames." *Proc. CIMS Conference, Baltimore, Maryland, 7-8 November.*

Blum, H.B. & Rasmussen, K.J.R., 2016c. "Experiments on long-span cold-formed steel double-channel portal frames." *Research report R962*. School of Civil Engineering, University of Sydney.

Blum, H.B. & Rasmussen, K.J.R., 2016d. "Finite element modeling and parametric study of cold-formed steel portal frames." *Proc. SEMC Conference, Cape Town, South Africa, 5-7 September.*

Kwon, Y.B., Chung, H.S., and Kim, G.D., 2004. "The Structural Behavior of Connections of Cold-Formed Steel Portal Frames." *Proc. Seventeenth International Specialty Conference on Cold-Formed Steel Structures, Orlando, Florida*, 761-775.

Lim, J. B. P., and Nethercot, D. A., 2002. "Design and development of a general cold-formed steel portal framing system." *The Structural Engineer*, November, 31–40.

McGuire, W., Gallagher, R., Ziemian, R., 2000. Matrix Structural Analysis, with MASTAN2, MASTAN2 v3.5 maintained at www.mastan2.com, last visited January 2016.

Robertson, A.P., 1991. "A study of base fixity effects on portal frame behaviour." *The Structural Engineer*, Vol 69 No. 2, January, 17-24.

Stratan, A., Nagy, Z., and Dubina, D., 2006. "Cold-formed steel pitched-roof portal frames of back-to-back plain channel sections and bolted joints." *Proc. Eighteenth International Specialty Conference on Cold-Formed Steel Structures, Orlando, Florida*, 351–365.

Wrzesien, A. M., Lim, J.B.P., Xu, Y., Dundu, M., MacLeod, I., Lawson, M., 2012. "Stressed Skin Effects on Cold-Formed Steel Portal Frames with Semi-Rigid Joints - Experimental study." *Proc. Sixth International Conference on Coupled Instabilities in Metal Structures*, 303–310.

Zhang, X., 2014. "Steel portal frames with locally unstable members." *PhD Thesis*. School of Civil Engineering, University of Sydney.